

Development of Sample Verification System for Sample Return Missions

Risaku Toda*, Colin McKinney, Shannon P. Jackson,
Mohammad Mojarradi, Ashitey Trebi-Ollennu and Harish Manohara†

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-393-5483

*Risaku.Toda@jpl.nasa.gov, †Harish.Manohara@jpl.nasa.gov

Abstract—This paper describes the development of a proof-of-concept sample verification system (SVS) for in-situ mass measurement of planetary rock and soil sample in future robotic sample return missions. Our proof-of-concept SVS device contains a 10 cm diameter pressure sensitive elastic membrane placed at the bottom of a sample canister. The membrane deforms under the weight of accumulating planetary sample. The membrane is positioned in proximity to an opposing substrate with a narrow gap. The deformation of the membrane makes the gap to be narrower, resulting in increased capacitance between the two nearly parallel plates. Capacitance readout circuitry on a nearby printed circuit board (PCB) transmits data via a low-voltage differential signaling (LVDS) interface. The fabricated SVS proof-of-concept device has successfully demonstrated approximately 1pF/gram capacitance change.^{1,2}

TABLE OF CONTENTS

1. INTRODUCTION.....	1
2. BACKGROUND	1
3. SENSOR DESIGN.....	2
4. PROOF-OF-PRINCIPLE TEST	4
5. CAPACITANCE READOUT CIRCUIT	5
6. SUMMARY	5
ACKNOWLEDGEMENT	6
REFERENCES	6
BIOGRAPHY	7

1. INTRODUCTION

In previous human lunar sample return missions (Apollo 11, 12, 14, 15, 16 and 17), astronauts were able to ascertain the quantity of lunar samples before returning to Earth. Robust in-situ sample acquisition verification (assured sample quantity (mass or volume)) systems would be critical to the next generation NASA robotic sample return missions. For sample return missions the Sample Transfer Chain (STC) would be responsible for the acquisition, verification, containment and transfer of the sample from the planetary body to the surface of the Earth. A key mission success criterion for robotic sample return missions would be that an assured sample quantity has been collected before the Earth-

return phase of the mission is initiated. For some robotic sample return missions sample acquisition verification must be done autonomously without ground in the loop of operations.

There is a technology gap for sample acquisition verification systems for robotic sample return missions. NASA's Genesis and Stardust robotic sample return missions successfully returned samples to Earth without an in-situ sample acquisition verification system (SVS) on board the spacecraft [1,2]. Positive confirmation of successful sample acquisition and transfer was done after the return of the sample capsule to Earth. These two missions are an exception because of the types of sample they acquired, no direct interaction with the target body was required and sample acquisition time was in order of several minutes. JAXA's Hayabusa mission also did not have an in-situ sample acquisition verification system; as a result, positive confirmation of successful sample acquisition and transfer could only be done after the return of the sample capsule to Earth [3]. The approach of providing positive confirmation of successful sample acquisition and transfer for robotic sample return missions after the return of the sample capsule to Earth is less than ideal since the ultimate goal of a sample return mission is to return an assured sample quantity (threshold science) to Earth.

This point argues for additional technology development for future sample acquisition verification systems for potential robotic sample return missions. In this paper, we present a novel in-situ SVS that is designed for integrated sampling systems that could survive and operate in challenging environments (extremes in temperature, pressure, gravity, vibration and thermal cycling) for real-time in-situ sample acquisition verification. The in-situ SVS would enable the unmanned spacecraft system to re-attempt the sample acquisition procedures until the capture of desired sample quantity is positively confirmed, thereby maximizing the prospect for scientific reward.

2. BACKGROUND

The primary objective of a sample return mission is retrieving pristine planetary sample without contamination. Spacecraft systems including the SVS must be designed so

¹ 978-1-4244-7351-9/11/\$26.00 ©2011 IEEE.

² IEEEAC paper #1302, Version 2, Updated December 16, 2010

that it will not contaminate the planetary sample. Even very small contamination may impact accuracy of elemental analysis such as isotopic age determination. For example, isotope composition analysis of Apollo 11 lunar sample required 0.005%-level precision [4]. Traditionally, a few materials such as stainless steel SUS 304 and Aluminum 6061 alloy have been used for planetary sample handling applications. Therefore, we use these materials exclusively for areas that may become contact with the sample.

Planetary/Moon environment is harsh for spacecraft components. Temperature change may exceed 100 Kelvin during a day mainly due to change of solar radiation. The SVS sensor must survive such a large temperature change. Careful choice of materials and design is necessary to build a robust SVS sensor that is stable against large temperature changes. Additionally, the SVS sensor should be designed so that planetary atmosphere and/or vacuum environment will not impact sensor performance.

There are several potential approaches to detect sample presence in robotic spacecrafts. For example, (1) Mass measurement by spring-mass system and transducers, (2) Optical methods such as photo imaging, (3) Inertia measurement by Newton's second law of motion. The SVS sensor development described here is intended for planets and moons where significant gravity exists. Microgravity asteroid sample return is not within the scope of this study. The inertia measurement is used for monitoring astronauts' weight in microgravity environment of International Space Station [5]. However, inertia measurement must apply thrust to the mass being measured and thus the system becomes relatively complicated. The optical methods such as photo imaging can observe the shape and color of planetary samples during sample acquisition. However, a photo image doesn't provide sample mass and the viewing aperture may be obstructed by dust covering the lens. Mass measurement by spring-mass system appears to be the simplest approach for sample weight measurement on the planets/moons.

Deflection of the spring in such spring-mass system can be detected by transducers such as piezoresistive and capacitive sensors. However, temperature sensitivity is an inherent disadvantage in piezoresistive sensors. For the planetary applications that undergo large temperature change (or cycles), capacitive method appears to have significant advantage.

The SVS sensor described here is an in-situ sensor that measures the sample weight during sample acquisition. It is desirable for the sensor to be integrated to the sample canister or cache. In other words, separate weighing station to measure canister weight is not an attractive option because it requires complicated maneuver by a robotic arm. The integrated SVS sensor will need to be designed lightweight, small volume and shock tolerant. This is because the sample canister is a primary payload of a return vehicle that would endure re-launch from planet/moon,

atmospheric entry, descent and landing phases upon return to Earth.

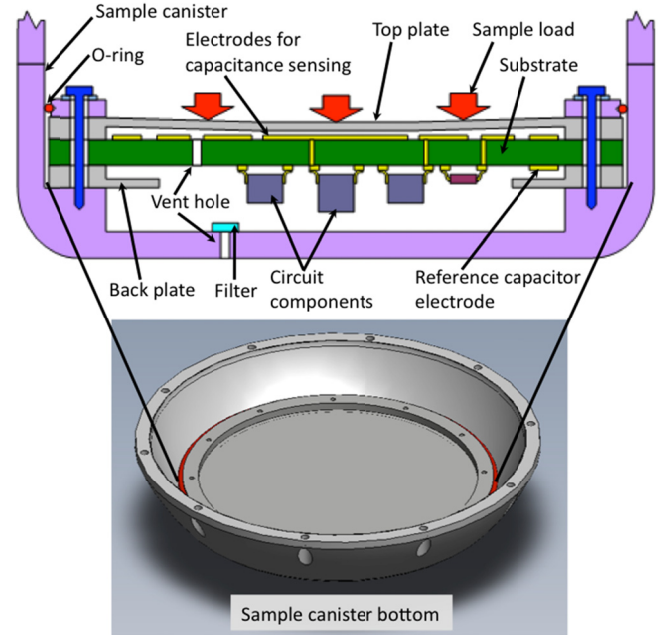


Fig. 1. Cross-sectional view of planetary sample mass sensor mounted at bottom of sample canister.

3. SENSOR DESIGN

Figure 1 shows a cross-sectional view of the sample mass sensor as it is mounted at the bottom part of a sample canister [6]. It is assumed the volume of sample canister is approximately 1 liter. Only the bottom section of sample canister is shown in Figure 1. The sensor is placed as a false-bottom and so that the weight of planetary sample is measured during the sample acquisition process. The top plate is a thin stainless steel SUS304 membrane that will deform by the sample load. The middle layer is a rigid substrate that has an array of electrodes on the top side. There is a narrow gap between the SUS304 top plate and the substrate allowing the deformation of the top plate to be capacitively detected. ICs and other discrete components for the capacitance readout are mounted on the backside of the substrate. There is an additional back plate just under the substrate. The shape of the two plates (top and bottom) is identical except that the bottom plate has a center hole to allow tall circuit components protrusion. The SUS304 back plate is used as a reference capacitance for calibration purposes. The stack of top plate, substrate and bottom plate is attached to the bottom of canister by an Aluminum 6061 retainer ring and pressure-loaded fasteners. Small gaps on the mounting hole absorb coefficient of thermal expansion (CTE) mismatch when the sensor is exposed to large temperature change. An o-ring placed on the side of retainer ring prevent small planetary sample particles from falling into narrow gaps on the edges of plates and substrate as this may cause sample contamination. Air vent holes equalize the cavity pressure to the ambient pressure. A microporous

filter is placed on the vent hole so that dust particle will not interfere with capacitive measurement.

The deformation of the SUS304 top plate is illustrated in Figure 2. Assuming a light and uniform loading (Figure 2-B), the deformation is relatively large at the center of membrane compared to the outside. Therefore, capacitance at the center (C_{ctr}) shows larger increase compared to the capacitance at the outside (C_{out}). When the applied load increases, the center portion of the membrane will touch the floor (Figure 2-C). The C_{ctr} is now shorted and becomes unable to measure, but the outside C_{out} is still available. Using a series of concentric distributed capacitors expands the overall pressure measurement range. Figure 2-D shows the membrane is experiencing extremely high load. In this case, the membrane is mostly touching and stopped at the underlying substrate and the capacitive readout is not functional. However, the membrane does not rupture easily because its mechanical strength is significantly reinforced by the underlying rigid substrate that prevents excessive strain. Therefore, the sensor can be made highly sensitive but robust against possible shocks that may be expected during launch and landing phases.

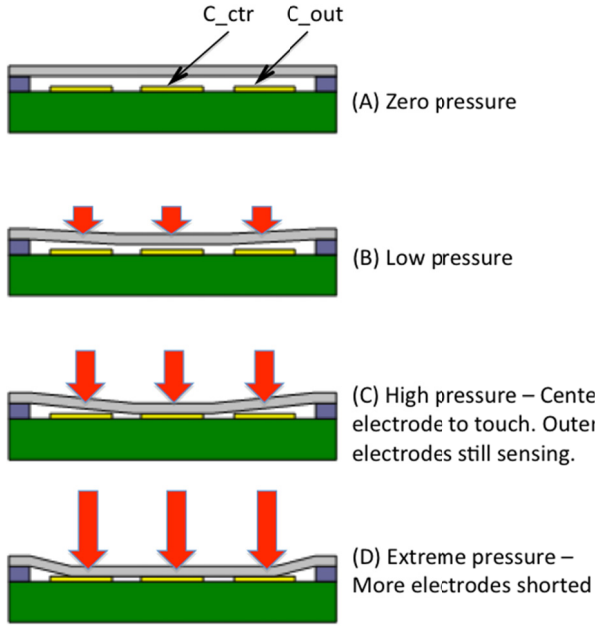


Fig. 2. Wide range sensing by distributed capacitors. (Not to scale)

FEM Analysis

The geometry of the pressure-sensing membrane is very similar to MEMS touch mode pressure sensors [7]. Originally based on Timoshenko's textbook [8], maximum deflection w_0 of a circular membrane at its center is expressed as:

$$w_0 = \frac{qr^4}{64D} \frac{1}{1 + 0.48 \frac{w_0^2}{h^2}}, \quad (1)$$

where q is the pressure, r is the radius, and h is the thickness of the circular diaphragm. D is flexural rigidity;

$$D = \frac{Eh^3}{12(1 - \nu^2)}, \quad (2)$$

where E is the Young's modulus, ν is the Poisson's ratio.

Assuming 0.1kg load is uniformly applied over a circular SUS304 plate with 90mm diameter (2x5mm=10mm is subtracted from membrane diameter 100mm due to the retainer ring on the edge), 200 μ m in thickness, maximum deflection is estimated as 66.8 μ m from equation (1). Here, the 0.1kg load is equivalent to 0.27kg sample load in Martian gravity and 0.6kg sample load in lunar gravity.

Figure 3 shows the deflection of the same SUS304 membrane under 0.1kg uniform load as calculated by ANSYS finite element analysis simulation. The obtained center deflection 68.6 μ m is reasonably close to the value calculated from Timoshenko's equation (1).

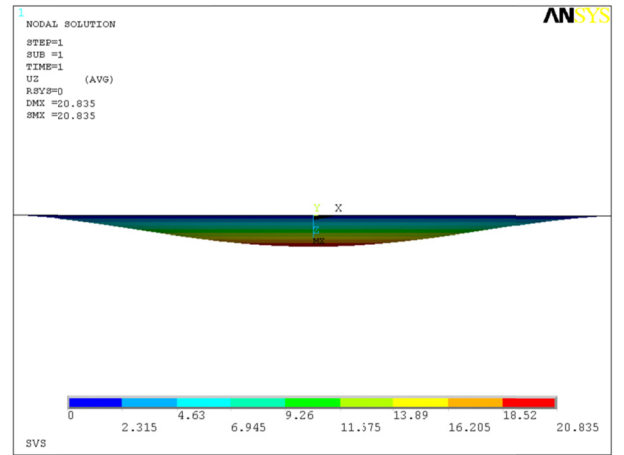


Fig. 3. ANSYS simulation. 0.1kg weight applied uniformly over the sensor surface. (z-axis scaling is exaggerated)

Figure 4 shows electrode pattern that was used in the first sensor prototype. Seven concentric electrodes are placed. Surface areas of seven electrodes are approximately equal so that the initial capacitance of the parallel plate capacitors will be identical. Capacitance of parallel plate capacitor is given by,

$$C = \epsilon \frac{A}{d}, \quad (3)$$

where ϵ is the permittivity, A is the area and d is the gap distance. Shield wires are placed between electrodes in order to reduce RF interference.

□

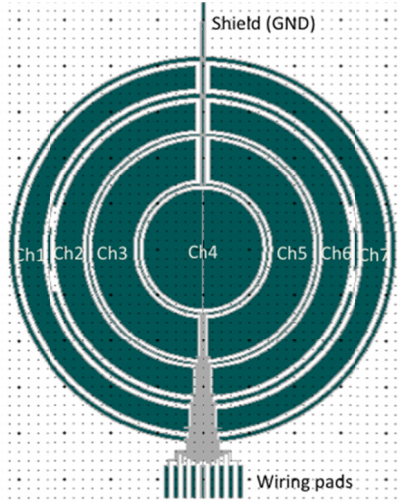


Fig. 4. Electrode pattern of first proof-of-principle prototype.

Based on the finite element analysis results, capacitance of these channels is estimated and plotted in Figure 5. The gap width is assumed as 100 μm and the load is applied uniformly. Due to the symmetry, channels 5, 6 and 7 results are omitted because they are identical to channels 3, 2 and 1, respectively. The center channel Ch4 ramps up the quickest and the capacitor become shorted at about 100 gram load when the top plate and electrode are in contact. The outer electrodes such as Ch1 ramps up relatively slow and it can measure 800 gram loading or above. Therefore, inner electrodes have higher sensitivity for a small loading range while outer electrodes have relatively low sensitivity over a wide range.

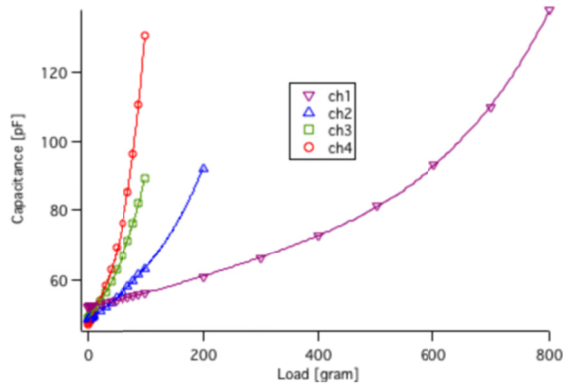


Fig. 5. Change of capacitance. (FEM simulation)

4. PROOF-OF-PRINCIPLE TEST

The first SVS mass sensor prototype is fabricated by using MEMS fabrication technique. Figure 6 shows a picture of the prototype substrate. A 100 mm diameter glass substrate is anodically bonded with thermally oxidized silicon wafer 100 μm in thickness. The silicon wafer is etched by Deep Reactive Ion Etch (DRIE) to form spacer ring at the edge of substrate. Metal electrodes are lift-off patterned on the glass

substrate. 200 μm to 500 μm thick SUS304 top plates are placed on top of the glass substrates for testing. Figure 7 shows the sensor prototype that is being tested by placing calibration weights on the SUS304 top plate.

Figure 8 shows a plot of capacitance change on this SVS sensor prototype. Actual thickness of the SUS304 membrane is 206 μm and the Silicon spacer thickness is 94 μm . Nearly uniform load is applied by placing numerous small weights evenly on the SUS304 membrane. The overall sensor characteristics appear to be similar to the finite element simulation result shown in Figure 5. The centermost channel Ch4 increases the quickest and the rate of capacitance change is approximately 1pF/gram when the load is less than 20 gram. The outer electrodes Ch1 and Ch2 ramps up well above the 100 gram load and demonstrate wide-range sensing capability of the mass sensor. However, the rate of capacitance increase is smaller at high-load range (>100gram) because the center of membrane is touching the glass substrates. Such contact mode is not included in the present finite element model. Other deviation from the finite element model may be attributed to small fabrication deviation (membrane thickness 206 μm as opposed to 200 μm in model, and initial gap 94 μm rather than modeled 100 μm , membrane warpage) and stray capacitance due to small wire/electrode overlaps.

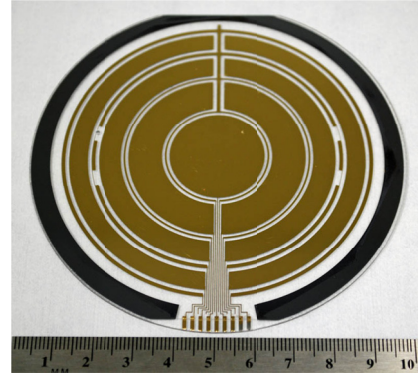


Fig. 6. Distributed electrode pattern on glass substrate.

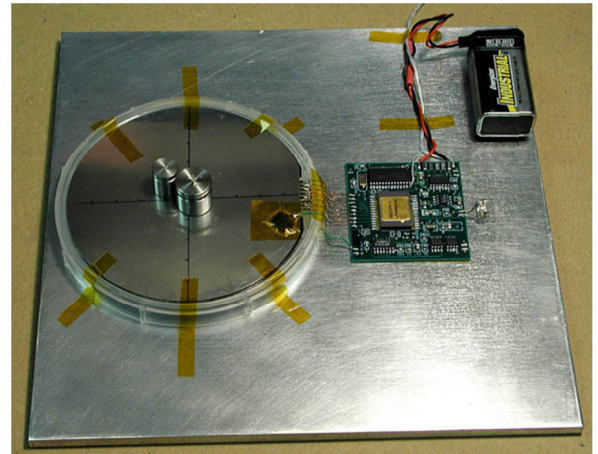


Fig. 7. Proof-of-principle sensor tested with calibration weights.

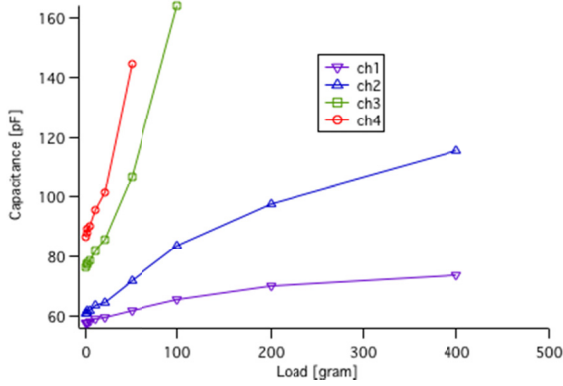


Fig. 8. Change of capacitance experimentally measured on proof-of-principle mass sensor.

Non-uniform loading

During the mass measurement of solid rock and soil, the sample may be distributed unevenly over the membrane. When a 0.1 kg mass is placed over a 20 mm diameter circle area at the center, maximum deformation is 204.6 μm as estimated by ANSYS simulation. This deflection is approximately three times larger compared to uniform loading of the same mass. Figure 9 shows another simulated example where the same 0.1 kg load is applied over 20mm diameter circle area that is 20 mm off-center. The maximum deformation is estimated as 150.9 μm and the deformed zone moved off-center to the right. Algorithm is currently being developed to accurately estimate sample weight by statistical approach coupled with robotic actuation mechanism to tilt the sample canister for moving solid sample within the canister.

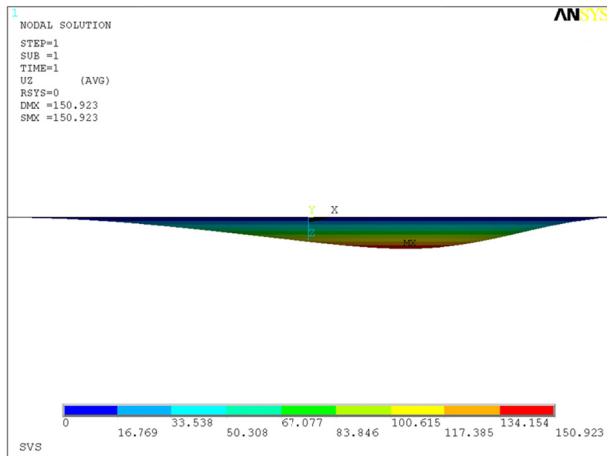


Fig. 9. ANSYS simulation of uneven loading. 0.1kg mass (20mm diameter circle footprint) placed 20mm off-center. (z-axis scaling is exaggerated)

5. CAPACITANCE READOUT CIRCUIT

The goal of the SVS capacitance readout circuitry was to provide in-situ mass sensing while consuming minimal

power and conforming to the extremely limited spatial constraints afforded to it. The sensor electronics are comprised of the capacitance readout circuitry, bi-directional communication to and from the host spacecraft, and power regulation for the active circuitry on the electronics board. The following paragraphs will describe electronics integration to the sensor itself, the method of deducing sensor capacitance and how this data is sent to the host spacecraft for processing.

The limited overall area and height in which the electronics reside created a spatial limitation in which the design would be constrained. The electronics are mounted directly beneath the sensor substrate in order to preserve signal integrity and provide an all-in-one solution for the mass sensor itself. The height limitation placed upon the electronics (less than 0.25 inch and falling towards the edges of the sensor) greatly handicapped component selection and called for a design with minimal part counts. The resulting circuit design was a simple circuit topology for sensing the capacitance of each of the seven channels and reporting the values of each sensor to the host spacecraft.

The theory of operation for the sensor electronics is that of a simple current source charging a capacitor. The sensor itself act likes seven discrete capacitors, where the top deformable plate functions as a common electrode connected to electrical ground for all seven capacitors. The positive electrode for each capacitor is then individually interfaced to the sense circuitry. A microcontroller commands an analog multiplexor (AMUX) to select between the seven sensor electrodes, as well as a temperature sensor and reference capacitor for calibration purposes. When a specific sensor electrode is targeted, a counter is started within the microcontroller and a precision current source charges the capacitor. The voltage is then monitored on its output by a fast comparator. Once the capacitor charge reaches the level of a precision reference voltage, the comparator changes states and signals the microcontroller to stop its running count. This count is then used to decipher the capacitance of the targeted sensor. This process is repeated for all seven capacitors and an accurate model of weight distribution and overall mass can be obtained by the spacecraft electronics.

The microcontroller utilizes a 16-bit counter that ultimately provides the resolution and accuracy of the capacitance measurement. When interfaced with the prototype sensor as seen in Figure 7, the readout electronics were able to provide a capacitance measurement with 0.1 pF resolution. The counter also allowed for a full-range capacitance sense of up to 4 nF with the aforementioned resolution across the entire range. The floor of the capacitance measurement is limited by the stray capacitance inherent to the PCB, component input capacitances, and the wires that connect the sensor to the electronics board. Figure 10 shows a top-level block diagram of the electronics board.

The capacitance value is computed for each of the seven channels of the sensor within the microcontroller. The microcontroller then outputs this data, in addition to ancillary data such as temperature and status, to the host spacecraft using a LVDS transmitter. A single +5V rail provided by the spacecraft powers the board and a linear voltage regulator creates the +3.3V necessary to operate the board.

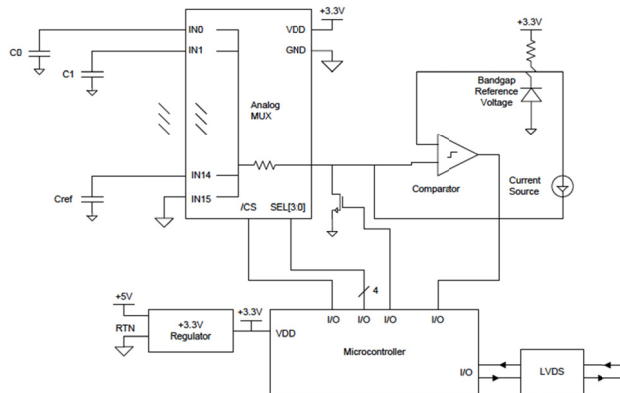


Fig. 10. Top-level block diagram of SVS electronics.

6. SUMMARY

A proof-of-principle sample verification system is developed. The objective of the sensor is to perform in-situ measurement of planetary rock/soil sample mass during sample accumulation. The sensor is designed to prevent sample contamination, to withstand large temperature change, to minimize weight and volume, and to have robustness against shock. The proof-of-principle sensor has shown high sensitivity of 1pF/gram at low mass range while maintaining capability to measure large mass. Further development will include building algorithm for estimating uneven sample loading, and use of PCB-based substrate for circuit integration. Also, environmental testing (thermal-vac, shock, etc.) will be performed for further validation toward future planetary sample return missions.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Don Hunter and Mr. Eduardo Urgiles for valuable suggestions. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

- [1] D. S. Burnett, B. L. Barraclough, R. Bennett, M. Neugebauer, L. P. Oldham, C. N. Sasaki, D. Sevilla, N. Smith, E. Stansbery, D. Sweetnam, R. C. Wiens "The Genesis Discovery Mission: Return of Solar Matter to Earth", *Space Science Reviews*, Vol. 105, pp. 509-534, 2003.
- [2] D. E. Brownlee, P. Tsou, J. D. Anderson, M. S. Hanner, R. L. Newburn, Z. Sekanina, B. C. Clark, F. Horz, M. E. Zolenski, J. Kissel, J. A. M. McDonnell, S. A. Sandford, A. J. Tuzzolino, "Stardust: Comet and interstellar dust sample return mission", *J. of Geophys. Res.*, Vol. 108, E10, 8111, doi:10.1029/2003JE002087, 2003.
- [3] J. Kawaguchi, H. Kuninaka, Fujiwara, T. Uesugi, "MUSES-C, Its launch and early orbit operations", *Acta Astronautica* 59, pp. 669-678, 2006, doi: 10.1016/j.actaastro.2005.07.002
- [4] D. A. Papanastassiou, G. J. Wasserburg, D. S. Burnett, "Rb-Sr ages of lunar rocks from the sea of tranquillity", *Earth and Planetary Science Letters*, Vol. 8, Issue 1, pp. 1-19, 1970 doi:10.1016/0012-821X(70)90093-2
- [5] J. J. Uri, C. P. Haven, "Accomplishments in bioastronautics research aboard International Space Station", *Acta Astronautica*, 56, pp. 883-889, 2005. doi:10.1016/j.actaastro.2005.01.014
- [6] JPL New Technology Report #47690.
- [7] W. H. Ko, Q. Wang, "Touch mode capacitive pressure sensors", *Sensors and Actuators* 75 (1999), pp. 242-251.
- [8] S. P. Timoshenko, S. Woinowski-Kreiger "Theory of Plates and Shells", McGraw-Hill, 1940.

BIOGRAPHY



Risaku Toda (Member, IEEE) received a B.S. degree in Applied Physics and a Ph.D. degree in mechatronics and precision engineering from Tohoku University, Sendai Japan. He also received a M.S. degree in materials science and engineering from University of California Los Angeles (UCLA). Prior to joining Jet Propulsion Laboratory, he worked for Ford Motor Company Japan Ltd. and Ball Semiconductor Inc. in Allen TX. Since 2003, he has been with Nano and Micro Systems group at NASA Jet Propulsion Laboratory. His research interests include fabrication of MEMS sensors, actuators and nanotechnology devices for aerospace applications. He holds several US patents.



Colin McKinney received his B.S. degree in Electrical Engineering from Cal Poly, San Luis Obispo in 2008 and is currently pursuing his M.S.E.E. at the University of Southern California while employed full-time at the Jet Propulsion Laboratory. He is a member of the Advanced Instrument Electronics group under Mohammad Mojarradi at JPL with a primary focus of analog and mixed-signal electronics design. He is also active in the research and development of the enabling technologies for low-noise extreme environment (wide-temperature, high radiation) instrumentation-quality circuit design and implementation.



Shannon P. Jackson received his B.S. in Electrical Engineering from the California Polytechnic University, Pomona and has been at NASA's Jet Propulsion Laboratory (JPL) since 1985. He has been instrumental in developing space flight hardware that has flown on Earth orbit and Mars missions, as well as developing and fielding neutrino detectors in Antarctica. His interests include micro-power applications of microprocessors, smart sensors, fiber optics, and wireless systems. He holds patents in the area of signal processing and wireless Sensor-Webs.



Mohammad Mojarradi (Senior Member, IEEE) is a Principal at Jet Propulsion Laboratory in Pasadena, CA. A Senior Member of IEEE, he was the chair of the IEEE San Fernando Valley Section and an integrated circuit design specialist. Specifically he is an expert in developing mixed-signal/mixed-voltage electronic circuits for smart power systems, sensors and micro-machined electromechanical interface applications. He leads a consortium of universities developing electronics for extreme environments and manages the development of the electronic circuits for the "thermal cycle resistant electronics" task for Mars Science Laboratory. He also has

an on-going collaborative effort on developing smart power integrated mixed-signal electronics for sensors, actuators, and power management and distribution systems. Dr. Mojarradi has over 20 years of technical, management and academic experience. He received his Ph.D. in electrical engineering from the University of California, Los Angeles (UCLA) in 1986. He has twenty-two patents, forty publications and is a member of IEEE. Prior to joining Jet Propulsion Laboratory, Pasadena, CA, he was an Associate Professor at Washington State University and the Manager of the mixed-voltage/specialty integrated circuit group at the Xerox Microelectronics Center, El Segundo, CA.



Ashitey Trebi-Ollennu (Senior Member, IEEE) is a technical group leader and robotics software engineer IV of the Mobility and Manipulation group at NASA Jet Propulsion Laboratory, California Institute of Technology, where he has been since 1999. He received his Ph.D. degree in control systems from Royal Military College of Science, Cranfield University, United Kingdom in 1996 and B.Eng. (Hons) from Queen Mary College, University of London, United Kingdom in 1991. He was a research scholar at Institute of Complex Engineered Systems, Carnegie Mellon University from 1997 to 1999. His research interest includes planetary rovers, manipulation, distributed mobile robotics, sensor networks, reconfigurable robots, mobile robot architectures, and man-machine interaction and has published widely in these areas. Dr. Trebi-Ollennu received the 2008 NASA Exceptional Engineering Achievement Medal for his contributions to the Mars Exploration Rover mission, 2007 Outstanding Engineer Award from IEEE Region 6, 2007 Sir Monty Finniston Achievement Medal from Institution of Engineering and Technology, U.K., and 2010 Specialist Silver Award from the Royal Aeronautical Society, U.K. Dr. Trebi-Ollennu is a Fellow of the Institution of Engineering and Technology, U. K., a Fellow Royal Aeronautical Society, U.K. and a Senior Member of the IEEE. He has served as a Guest Editor of the IEEE Robotics and Automation Society Magazine.



Harish M. Manohara (Member, IEEE) received the Bachelor of Engineering degree in instrumentation technology from the Bangalore University, India in 1989, followed by an M.S. degree in nuclear engineering in 1992, and a Ph.D. degree in engineering science in 1997 from the Louisiana State University, Baton Rouge, Louisiana. He joined the Center for Advanced Microstructures and Devices (CAMD) at the Louisiana State University as a Research Associate in January of 1997. In 1998, he became the Assistant Professor of Research at CAMD, and an Adjunct Faculty Member of the Department of Electrical Engineering. While at CAMD, he developed new X-ray microfabrication techniques. In November of 2000 he joined the Jet Propulsion Laboratory to develop advanced

silicon and vacuum electronic devices for THz applications. Since 2005, he has been leading the Nano and Micro Systems (NAMS) group at JPL and has developed carbon nanotube field emitters, nanoelectronic devices, miniature spectroscopic instruments, and MEMS for space, defense, medical, and commercial applications.

